Section F. Technology Roadmap and Program Formulation

F.1 Overview

The technology development effort for LISA builds upon years of experience with ground-based gravitational wave detectors. A detailed technology plan was written and reviewed by an independent panel in 1999. The LISA Project Office, formed in 2001, implemented and builds upon this plan. The current plan includes the following features:

- All critical technologies are identified and are directly linked to science requirements.
- No new inventions are required.
- Parallel and coordinated development paths with clear off-ramps are in place to ensure successful maturation of the technologies.
- Experts from around the world and their state-of-the-art facilities participate.
- All technologies are at a Technology Readiness Level (TRL) of at least 6 by 2006.

The plan identifies the critical technologies required to meet the mission science requirements. The baseline design of LISA does not call for any new “inventions” in the sense that all the advanced technologies have been used in other missions / applications, but with lesser performance or functionality. All the critical technologies are currently at a TRL of 3 or higher and are matured to a TRL of at least 6 by 2006.

The LISA technology program is specifically designed to address the required performance increase across the necessary technologies. To ensure success, the technology roadmap includes several parallel, yet coordinated efforts in both the U.S. and in Europe. A strong connection exists between technology development, modeling and system engineering to provide numerous development off-ramps (Figure F-1).

The plan includes two types of off-ramps for each technology item. First, margin between the minimal and baseline mission can be used as an off-ramp. For example, a 20% shortfall in laser power results in a decrease in instrument sensitivity by 10%. This is modest compared to the factor 10 margin between the nominal and minimal missions. This margin provides the off-ramp to stop the effort to increase laser power if the development effort fails to show sufficient progress towards a full powered laser.

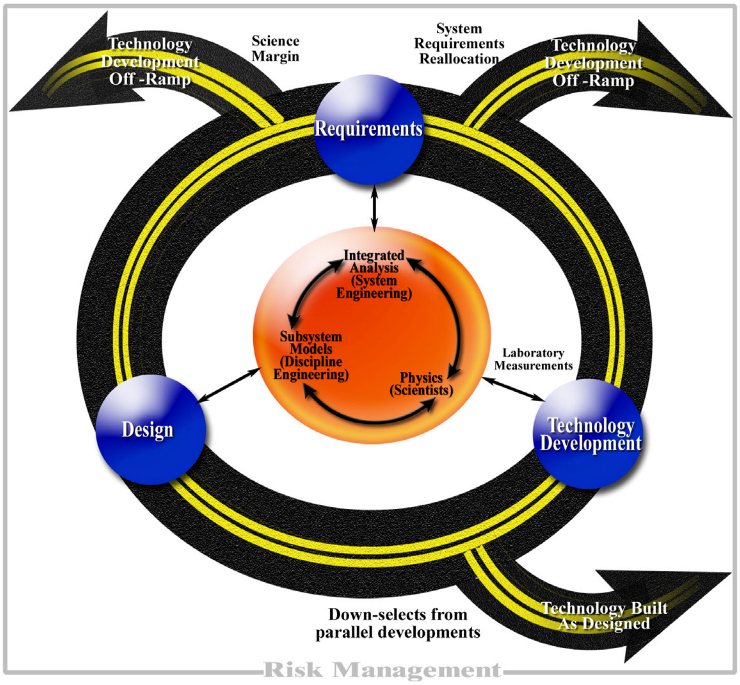


Figure F-1: Technology development off-ramps are gained by weaving technology development into the system engineering process

System trades can also be used as off-ramps by reallocating requirements to make up for a short falling. For example, the diameter of the telescope can be increased to compensate for the lower laser power discussed above. This will increase the pointing requirements and the size of the payload. If there is sufficient margin in these areas, this off-ramp can be used to end the laser development.

The required sensitivity of LISA to gravitational waves is directly derived from the science requirements (see Section D). The design sensitivity for the current baseline of LISA depends on four parameters:

- Disturbance accelerations
- Measurement sensitivity
- Arm length
- Integration time

Two of the three technology development elements directly address these critical parameters (see Figure F-2). The *Disturbance Reduction System* (DRS) includes technologies related to the disturbance accelerations parameter. These are the gravitational reference sensor (GRS), µN thrusters, and drag-free control laws. The *Interferometry Measurement System* (IMS) includes technologies related to the measurement sensitivity parameter. These are the laser, Phase Measurement System, frequency noise corrections, and ultra-stable structures.

The third element of the technology development effort addresses the *System Ground Verification* program. These include system test bed technologies and integrated modeling. The integrated modeling plays a particularly central role by tying all these efforts together and weaving them into the system engineering process. The modeling team is composed of both engineers and scientists and has strong ties to the Technology and System Engineering offices to ensure the technologies being developed are relevant to LISA and meet the system-level performance requirements. The modeling team also performs many of the trade studies that provide off-ramps for technology efforts.

Figure F-3 shows an overview of the technology development efforts. Key risks and mitigation steps have been identified for each technology item. Coordinated parallel development paths in both the U.S. and Europe are utilized as a risk mitigation step for those items with the greatest risk. This reduces the chance of failure of any path due to technical, schedule, or budget problems.

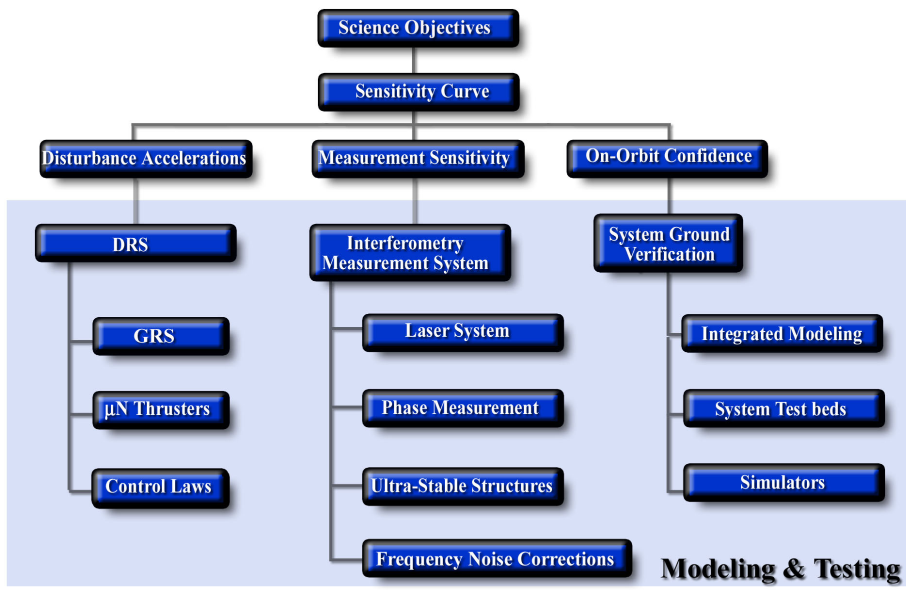


Figure F-2: The Technology Development effort is directly tied to achieving the science requirements.

The progress from red to green of all the technology items is carefully tracked and reviewed. Some paths may be terminated early if a parallel path demonstrates sufficient performance and maturity. The off-ramps discussed above also provide a means of concluding a development line. Firm down-select dates are identified where only the most promising technology is carried forward to implementation (see Section F.3 for down-select process). There is enough margin in the schedule to allow additional testing after the down-select for those items that require long lifetime demonstrations or a merging of several development paths (see detailed schedules in Appendix H-2).

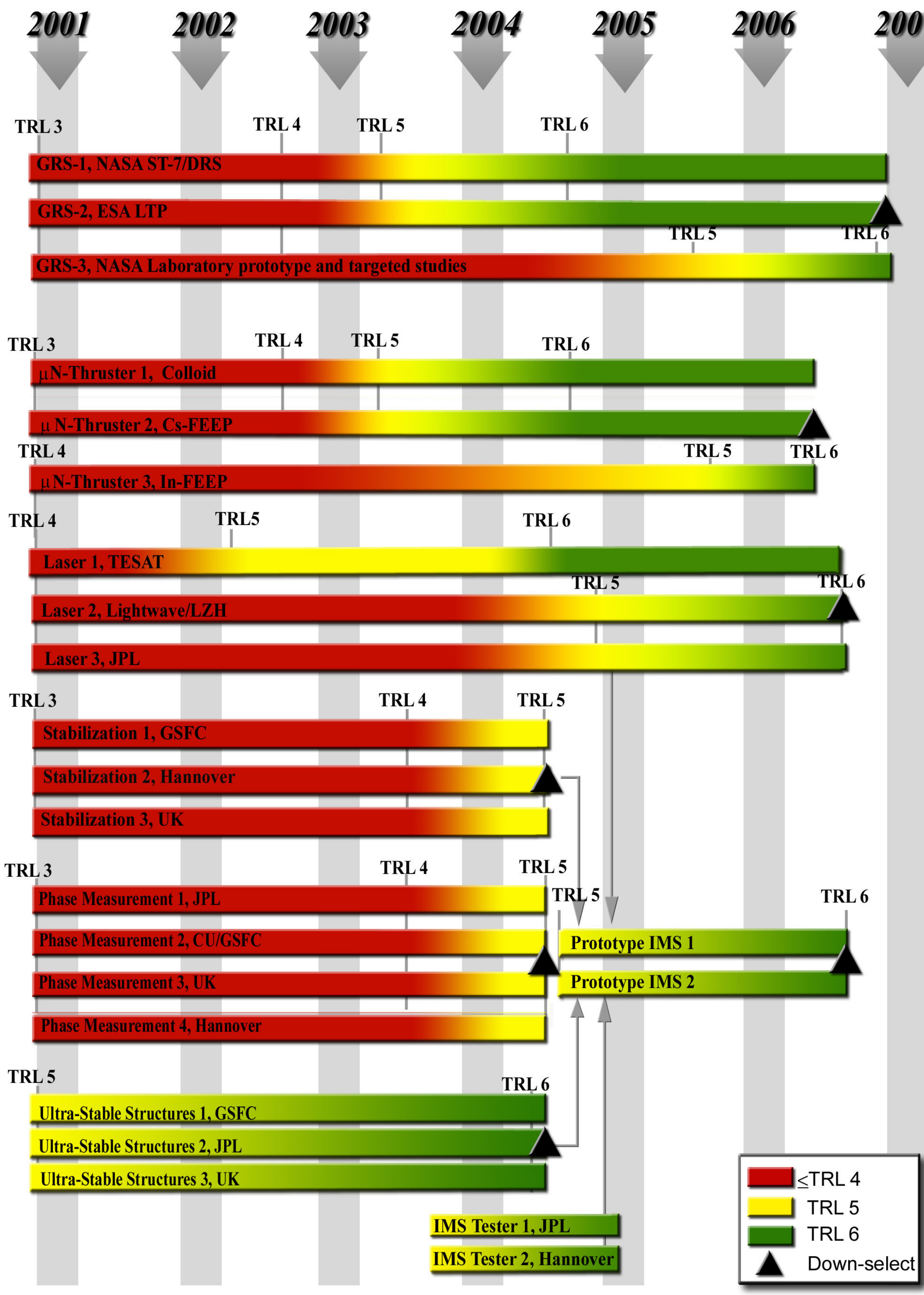


Figure F-3: The technology roadmap mitigates the risk of any single failure by carrying several parallel coordinated activities for the technology items with the most risk.

F.2 Technology Development Items

The following subsections describe the three classes of technologies introduced above. These three classes represent the top three elements of the technology development WBS. Each subsection discusses the current status of the technology, both in maturity (TRL) and performance, as well as describing the roadmap for achieving TRL 6 by 2006. The key risks and mitigation steps for each technology item are also described.

F.2.1 Disturbance Reduction System

The Disturbance Reduction System (DRS) on LISA provides a proof mass for the interferometric measurement that is free of disturbances to a level of accelerations that meets the top-level disturbance requirement of $3x10^{-15}$ $m/s^2/\sqrt{Hz}$ in the LISA Measurement Bandwidth (MBW). The DRS consists of three components: 1) the Gravitational Reference Sensor (GRS), which includes the free falling proof mass (PM) in its housing; 2) μN thrusters; and 3) DRS controls. The GRS provides an error signal to the DRS control that commands the μN thrusters to maneuver the spacecraft so as to keep the GRS housing centered on its proof mass.

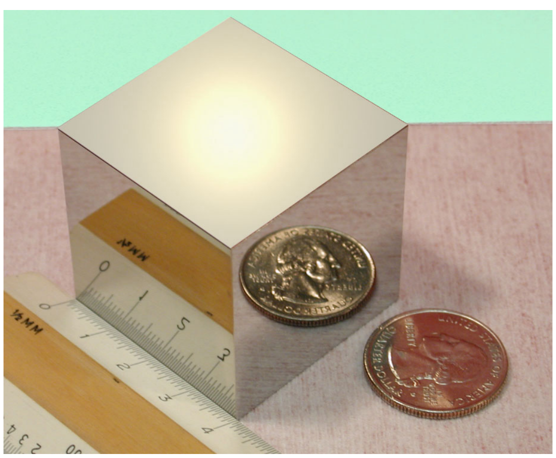


Figure F-4: The GRS proof mass is made of a platinum-gold alloy that has a near-zero magnetic susceptibility.

The gravitational wave signal is obtained by measuring the change in separation between the proof masses on the widely separated spacecraft. As shown in Figure F-4, a gold-platinum alloy is the material of choice for the PM due to its near-zero magnetic susceptibility. Each PM is a few centimeters on a side and has a mass of about 2 kg. They are gold-coated and polished to reflect at least 98% of the laser light.

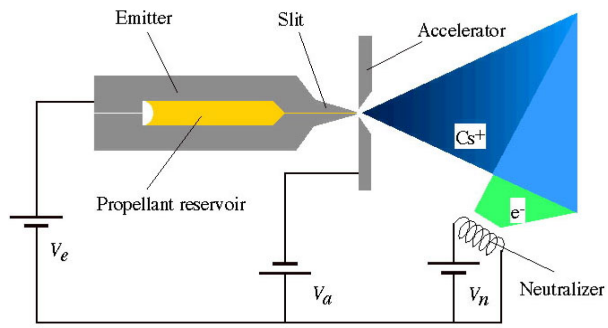


Figure F-5: The FEEP thruster operates by accelerating metal ions using a strong electric field.

The GRS uses electrostatic actuation and capacitive sensing to monitor and control the PM position relative to the spacecraft. The PM housing shields it from all external disturbances. A very high vacuum and thermally stable environment are maintained and the PM charge is controlled with ultraviolet light. A mechanical caging system is used to hold the PM during launch. During science operation the PM is freely floating within its housing and does not make physical contact with the housing walls.

The signals from the GRS are used to command μN thrusters that provide spacecraft actuation in 6 degrees of freedom. The baseline μN thrusters are field emission electric propulsion (FEEP) devices that deliver *continuous* thrust of tens of μNs with less than a tenth of a μN of thrust noise. FEEP thrusters use a liquefied metal propellant (typically indium or cesium) from which ions are extracted and accelerated by an electric field (Figure F-5). Both cesium and indium FEEP thrusters have demonstrated the LISA thrust noise requirements from ion current measurements. The emitter provides the ions and holds the propellant. The metal is fed to a needle or slit using capillary action so no feed mechanism is required.

A neutralizer is located nearby and provides charge control to the plume and prevents the spacecraft from charging up. A power processing unit provides control over the several voltages required. FEEP thrusters typically have a specific impulse of the order 10,000 seconds thus only a few grams of propellant are required for the lifetime of the mission.

The DRS controls utilize several decoupled feedback loops to maintain the spacecraft centering on the PM, ensure each PM is drag-free on the line-of-sight axis, and point the telescopes accurately and stably. Control strategies are needed to ensure the various control loops interact cooperatively to achieve the pointing and positioning requirements of the LISA mission. These strategies dictate (a) the level of interaction between the various control loops, i.e., whether one or more loops should be designed and/or implemented separately (decentralized control); and (b) the extent of the control authority within individual loops, i.e., whether active control is enabled in a given direction(s) and to what extent. Moreover, control strategies are required to deal effectively with the point ahead control: the outgoing beam is pointed ahead of the incoming beam since the distant spacecraft will have moved during the 16 seconds it takes for the outgoing beam to reach it.

F.2.1.1 Technology Readiness

The technology for the GRS is derived directly from space accelerometers. The primary difference between the GRS and an accelerometer is the size of the gap between the proof mass and its housing. Accelerometers require a small gap for strong coupling to spacecraft motion while the GRS requires a wide gap to reduce gap-dependent disturbance forces. A number of relevant accelerometers have flown in space including: the STAR accelerometer (Figure F-6) currently flying on the CHAMP satellite [Ref. F-1] and the SuperSTAR accelerometer currently flying on the GRACE satellite [Ref. F-2]. The SuperSTAR accelerometer is a modified version of the ASTRE accelerometer previously flown on several Space Shuttle missions (STS-78, STS-83, and STS-94).

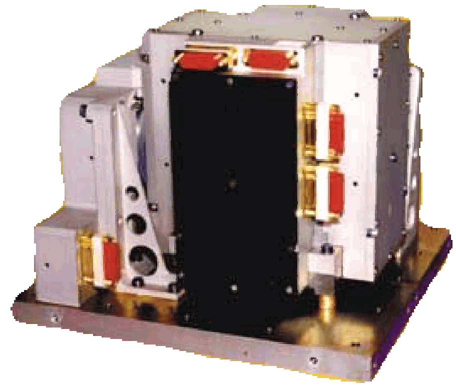


Figure F-6: The STAR accelerometer, currently flying on the CHAMP spacecraft, demonstrates many of the critical features of the GRS.

Most of the components of the GRS are space qualified for use in the accelerometers. Due to the system-level utilization of these technologies in this application, a TRL of 3 was assigned to the GRS at the beginning of the LISA technology development effort.

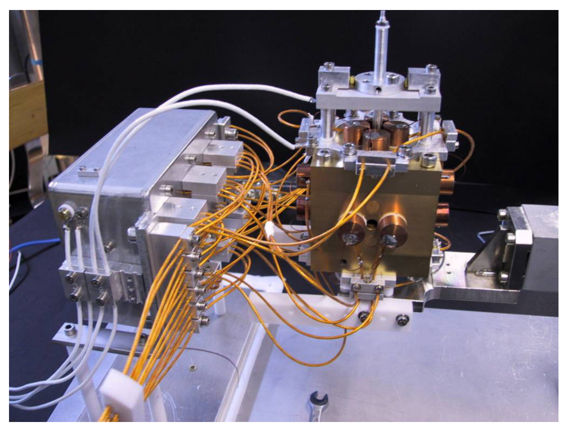


Figure F-7: A laboratory prototype of the GRS was built and is being tested in the torsion pendulum facility at the University of Trento.

Since then, a prototype GRS was built in Europe and has been tested at the University of Trento (see Figure F-7 and Figure F-16). Using an ultra-sensitive torsion pendulum, the prototype demonstrated a residual acceleration of $5x10^{-11}$ m/s^2√Hz. This level of disturbance was due to thermal motions of the apparatus, *not* limitations of the GRS. Additional analysis and measurements of specific disturbance effects indicate that the design of the GRS meets the LISA requirements. Therefore, a TRL of 4 is assigned to the current status of the GRS. The total project investment to date in the GRS is about $7.6M.

The indium FEEP thruster (Figure F-8) developed by the Austrian Research Centers Seibersdorf (ARCS) has flown as an ion source for spacecraft charge control instruments on a number of missions including the GEOTAIL [Ref. F-3] and CLUSTER-II [Ref. F-4] spacecraft. Laboratory prototypes of the Austrian indium FEEP as well as an Italian cesium FEEP (Figure F-9) existed at the start of the LISA technology development effort. Not all critical LISA requirements were demonstrated so a TRL of 3 was assigned.

Since then, noise measurements of the ion current have indirectly demonstrated the LISA thrust noise requirement of 0.1 $\mu N/\sqrt{Hz}$. Lifetime tests of the FEEP emitters are currently underway. The Austrian FEEP has demonstrated over 4000 hours of continuous operation. A TRL of 4 is, therefore, assigned to the current status of the μN thrusters. The total project investment to date in μN thrusters is about $3.6M.

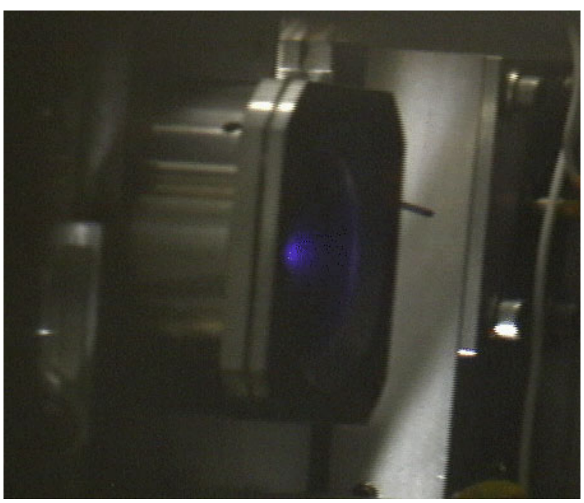


Figure F-8: An indium FEEP thruster on CLUSTER-II has been on-orbit since August 2000.

The DRS controls are not assigned a TRL, but similar decoupled feedback control algorithms implemented in digital computers are TRL 9. Since the beginning of the LISA technology development effort a detailed simulation of the LISA control system was developed and was shown to meet all requirements with margin [Ref. F-5]. The total project investments to date in DRS control laws is about $700k.

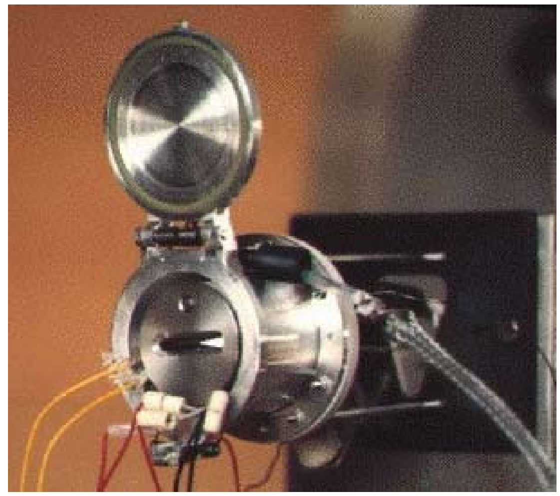


Figure F-9: The cesium FEEP Thruster developed by Centrospazio is part of the European package on SMART-2.

F.2.1.2 Technology Development Plan

The major risks for the DRS are summarized in Table F-1. The first risk is that the disturbance level on the GRS proof mass cannot meet the LISA requirement. This risk has a severe impact on the science. To mitigate this risk there are three coordinated but independent development efforts, one in Europe and two in the U.S. These three programs have regular coordination meetings to ensure the sensors are sufficiently different to maximally investigate the trade space.

In addition to the full sensor builds, a number of laboratory experiments are underway to systematically study and eliminate the leading disturbance effects. These include studies of patch fields, PM charging, gravitational gradient, magnetic effects, and thermal effects. Patch effects (the interaction of charge patches on the PM and housing surfaces) are specifically being targeted for investigation early and can be mitigated through GRS design with larger proof mass/ housing gaps. The other residual forces are being experimentally measured and are tracked through the design via the LISA integrated model.

Clear identification and characterization of these effects allow the extrapolation of performance from ground measurements of the GRS to on-orbit performance. A full system test of the GRS is performed on the ground to the degree possible given the Earth's gravity and environmental disturbances. A final demonstration of this extrapolation is performed using the two sensor packages on SMART-2 (see Section F.2.1.3).

The integrated model is essential for bridging the gap between ground and on-orbit performance of the GRS. The targeted laboratories studies and other test bed results feed the models to ensure they represent the appropriate physics.

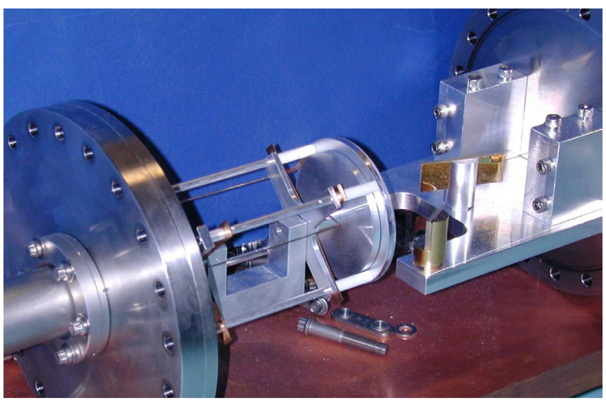


Figure F-10: A world-class torsion pendulum at the University of Washington is being used to study patch fields and other GRS disturbance effects.

The targeted GRS studies require the use of special tabletop scale equipment and facilities. For example, patch field studies are being performed using a torsion pendulum at the University of Washington (Figure F-10). A GRS simulator is also required to test the electrical interface and perform hardware in-the-loop control law simulations. No special GRS production facilities are required other than the readily available clean rooms at both NASA and ESA facilities. A GRS test bed already exists at the University of Trento (Figure F-17) and the construction of a similar setup is part of the NASA technology plan.

There are two key risks associated with the μN thrusters. First is that the thrusters will not meet the required thrust noise requirement. The impact of this risk is increased gain requirement on the DRS control laws. To mitigate this risk, three independent thruster technologies are being developed (cesium-FEEP, indium-FEEP, and colloid thrusters) and early testing of thrust noise is being performed. Indirect thrust noise measurements already indicate that the current thruster designs meet the LISA requirements. Direct thrust noise measurements are also underway at GSFC to confirm these results.

The second risk associated with the thrusters is that of not meeting the lifetime requirement. The impact of this risk is a shortened mission lifetime. To mitigate this risk, three independent thruster technologies are being developed and lifetime testing will begin early in the development cycle. Given that there is ample mass and power margin, this risk can also be mitigated by increasing the number of redundant thrusters on the spacecraft.

Production facilities for the thrusters already exist at the manufacturers. Performance, contamination, and EMI/EMC measurements can be made at existing facilities at GRC, GSFC, and JPL. Lifetime testing is already underway at the manufacturers and an independent lifetime test is part of the technology plan that requires a dedicated chamber for the duration of the test.

At the beginning of the technology development effort, the control laws carried the risk of not meeting the disturbance requirements. This risk has been largely retired using a detailed simulation of the LISA control system [Ref. F-5]. This risk will continue to be tracked until the GRS and μN thrusters have demonstrated the required performance. Hardware-in-the-loop tests of the control system are planned to verify the system performance and fully retire this risk.

F.2.1.3 Role of SMART-2

Both the NASA and ESA technology programs independently validate and verify all mission requirements including full system verification before launch. Additionally, ESA has chosen to sponsor a demonstration mission, SMART-2, for the most innovative aspects of the technology for LISA.

SMART-2 consists of one spacecraft and two payloads. The mission demonstrates drag-free flight with a residual acceleration noise of the proof mass below 3×10^{-14} $m/s^2/\sqrt{Hz}$. SMART-2 is currently undergoing parallel Phase B development by two contractors for launch in 2006 – two years prior to LISA Phase C/D.

ESA is providing the SMART-2 spacecraft, launch, and operations. The European payload, "LISA Test Package" (LTP), is being provided by European member state contributions. ESA invited NASA to join SMART-2 and provide the second payload. NASA participation is now funded under the New Millennium Program as ST-7. Each side provides an instrument package that best demonstrates three key technologies: GRS, μN thrusters, and drag-free control laws.

ESA and NASA develop their instrument packages in independent, but coordinated ways. Information is freely shared in order to mutually learn during the parallel development process. The LTP, ST-7, and LISA teams meet on a regular basis to ensure that LISA gets the maximum benefit from these activities. In addition, many members of the LISA project are also working on LTP or ST-7.

Each technology package contains two proof masses and an interferometer to measure their motion relative to each other and to the spacecraft. Depending on the operational mode, at least one of proof masses is free of residual acceleration noise to a level below 3×10^{-14} $m/s^2/\sqrt{Hz}$. This level of performance exactly meets the LISA minimum mission requirement.

Each set of μN thrusters provides spacecraft actuation in 6 degrees of freedom. The thrusters compensate for the ~20 μN of force due to solar radiation pressure and provide the actuation for the drag-free control. A number of control scenarios are demonstrated on SMART-2 including drag-free control using inputs from one GRS as well as a combination of two sensors (one from LTP and one from ST-7).

NASA participation in SMART-2 reduces risk by providing:

- A demonstration of alternate LISA GRS approaches at the level of the minimum mission.
- A demonstration of alternate LISA thruster approaches. (Although these can be fully demonstrated at the baseline mission level on the ground.)
- An opportunity for both teams to design, qualify, test, and launch key LISA systems in a competitive but cooperative environment.
- An opportunity to reach TRL 8 for both the GRS and the thrusters at the minimum mission level.
- A dress rehearsal for the LISA management team. The entities and many of the people are the same.

The SMART-2, LTP, and ST-7 programs are already underway. A summary of their major milestones is shown on Foldout G-2. The total investments to date by these projects are: $7.0M for SMART-2, $5.3M for LTP, and $3.0M for ST-7. The investments for the specific technologies cited elsewhere in the text already include these investments from LTP and ST-7.

Table F-1: The key risks for the disturbance reduction system are identified. The mitigation steps in place reduce the likelihood to low.

Risk	Impact	Mitigation	Consequence
GRS does not meet disturbance requirement	Severe impact to science	Three independent but coordinated development efforts. Targeted studies of disturbance effects. Precision GRS ground system test. Torsion pendulum measurement taken in 2002 met the ground verification requirement.	Severe
μN thrusters fail to meet lifetime requirement	Shortened mission lifetime	Three independent thruster technologies. Early lifetime testing. Increase redundant thrusters on spacecraft system trade.	Moderate
μN thrusters fail to meet thrust noise requirement	Increased gain requirement on DRS controls	Indirect thrust measurements of two FEEP technologies completed in 2001 met the thrust noise requirement. Three independent thruster technologies. Direct thrust noise measurements underway. Increase gain in DRS control system trade.	Minimal
DRS controls do not meet disturbance requirement	Moderate impact to science	19 degree of freedom control simulations completed in 2002 demonstrated the required disturbance reduction. Complete DRS controls simulation. DRS simulator with hardware-in-the-loop. Increase cross-coupling requirement on GRS system trade.	Moderate

F.2.2 Interferometry Measurement System

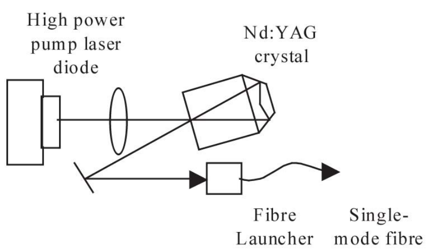
The Interferometry Measurement System (IMS) is the "yardstick" for measuring the change in separation between the distant proof masses due to passing gravitational waves. The IMS measurement sensitivity derived from the science requirements is 40 pm/√Hz. Laser interferometry is a very advanced field of study and the technology for the LISA IMS can be drawn from years of research in this area. Ground-based gravitational wave antennae have demonstrated many of the aspects required for the LISA IMS, and the strategy for bringing this technology to LISA is to draw upon the experience of this community and adapt their techniques for this application.

The IMS is composed of a laser system, optical system, phase measurement system, telescope, laser and clock frequency noise corrections, and structures. The majority of the IMS can be fully tested on the ground. The IMS development schedule is primarily driven by the requirement for adequate lifetime testing of the laser system.

The baseline design of the IMS calls for a 1 W laser that is continuously tunable over 10 GHz. The high levels of frequency stability required of the LISA laser mean only diode-pumped solid-state lasers are suitable as the light source. Current state-of-the-art semiconductor lasers offer neither the levels of frequency stabilization required for LISA nor a way to adequately stabilize the frequency.

Currently, two options are being considered as the light source for LISA. Each type is a variation of a diode pumped solid-state laser:

- Non-planar ring oscillator (NPRO)
- Master oscillator with power amplifier (MOPA)



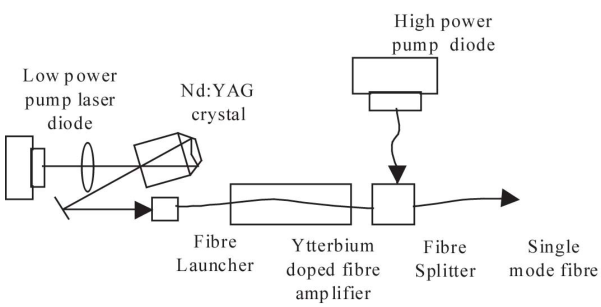


Figure F-11: Both the NPRO (top) and MOPA (bottom) laser configurations are currently available in non-space qualified versions.

A schematic of both laser types is shown in Figure F-11. NPRO lasers are commercially available in non-space qualified versions that meet LISA requirements: from Lightwave Electronics and Laser Zentrum. Bosch is near to offering a commercial MOPA laser.

The NPRO laser incorporates a high power pump laser diode pumping a monolithic Nd:YAG crystal (the facets of the crystal form the laser cavity). This laser has the advantage of a simple, compact design, however at the expense of requiring a high power pump diode, the lifetime of which is a cause of concern. As the absorption band of Nd:YAG is rather narrow, it is necessary to control the frequency of the pump light. This is accomplished by stabilizing the temperature of the pump diodes.

The MOPA design incorporates a similar NPRO, but at a much lower output power. The light from this master NPRO is amplified using a ytterbium doped fiber amplifier. As the absorption band of ytterbium is much broader than that of neodymium; the high power pump laser diode for the amplifier may not need to be temperature stabilized.

One of the inherent benefits of an equal arm interferometer is that frequency fluctuations of the light source will exactly cancel when the two beams are combined. Although LISA will have arm lengths that are approximately equal, orbital variations will introduce length imbalances of around 1%. Under these circumstances laser frequency noise will not exactly cancel. The solution to this problem is two-fold. First, the laser is pre-stabilized by frequency locking to a reference cavity (Figure F-12) or molecular line, and second, residual frequency noise in the output is eliminated by post-processing using a technique called Time Delayed Interferometry (TDI).

The laser frequency stabilization can be realized in at least two ways:

- Pound-Drever-Hall locking to an ultra-stable frequency discriminator cavity.
- Laser frequency stabilization to a hyperfine transition of molecular Iodine.

The Pound-Drever-Hall scheme has significant heritage in the gravitational wave community: all lasers used in ground-based, long baseline interferometers are stabilized using this scheme. Peterseim, *et al.,* also successfully applied this technique to a laser in the LISA configuration [Ref. F-6].

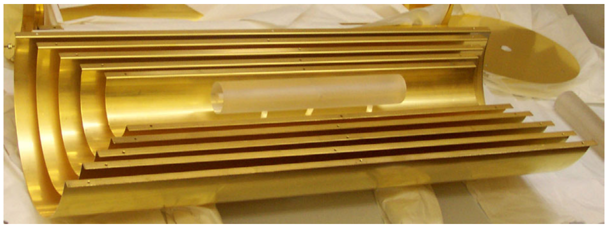


Figure F-12: Laser frequency stabilization has been demonstrated to nearly the LISA requirements using a thermally isolated reference cavity.

Locking the laser frequency to a hyperfine transition of molecular iodine has also been demonstrated in the lab to the levels required for LISA. Iodine stabilization has the advantage of being an absolute frequency standard with excellent long-term stability. Iodine stabilized Nd:YAG lasers are being developed at the National Institute of Standards and Technology (NIST) in Colorado.

After pre-stabilization, the remaining laser frequency noise couples to the output of each phase meter with a well-defined transfer function. This transfer function depends on one parameter – the travel time of the light between spacecraft. If this transfer function is known accurately enough the LISA signals can be processed in a way such that the frequency noise at the output is negligible.

TDI is an elegant technique which implements the processing in real time, by the simple subtraction of the data streams with appropriate delays [Ref. F-7]. An alternative to TDI exists that does its calculations in the Fourier domain, but it is more complex to implement and does not have as good performance [Ref. F-8].

A major advantage of TDI is that it provides several different outputs with the laser frequency noise removed. The most basic are three outputs that represent the frequency noise-free Michelson-type interferometer. Three Sagnac-type interferometer combinations can also be constructed with removed laser frequency noise. A noise-dominated output has been shown to have only very weak coupling to the gravitational wave signal yet has the same magnitude of coupling to the instrument noise. This is an invaluable tool in characterizing the instrument performance in flight and should provide increased confidence levels for the gravitational wave event detection. Together the Sagnac and noise-dominated signals form a basis of all possible readouts for the LISA interferometer.

The laser beam in LISA is *not* reflected off the proof mass and sent directly to the distant spacecraft as in a standard interferometer. Instead, each spacecraft acts as an optical transponder, re-transmitting a phase-locked copy of the incoming beam back to the original spacecraft. When the returning and outgoing beams are beat together, there is a significant frequency difference between the two beams, originating from the Doppler shift imparted onto the light as it traverses the arm (twice). This frequency difference will be of the order of tens of MHz. The phase readout system of LISA must be able to record this signal with a sensitivity of 5×10^{-5} cycles/$\sqrt{\text{Hz}}$.

Currently there are two phase measurement schemes being investigated for LISA. One scheme relies on a phase-locked-loop (PLL) approach, similar to that used in GPS receivers. The second approach relies on counting the phase changes using a very fast clock.

A final aspect of the IMS that requires technology development is the stability of the materials and bonds holding the optical components and the structure of the telescope (the telescope itself is not considered a technology development item). Material length changes due to thermal fluctuations and material creak can enter into the measurement through direct changes of the optical path length of the interferometer arm length, changes to the wavefront curvature of the transmitted beam (e.g. by changing the “focusing” of the telescope by changing the primary-secondary separation), and changes to the length of the reference cavity (and thereby degrading the frequency stabilization performance). A number of precision experiments are currently underway to test the telescope and optical system materials and bonds to levels that meet the LISA requirements.

F.2.2.1 Technology Readiness

Lightwave Electronics has space qualified a NPRO laser for the Tropospheric Emission Spectrometer (TES) instrument on the Aura spacecraft [Ref. F-9] as shown in Figure F-13. This laser uses the same design as an equivalent laser for LISA, however the output power is much lower (0.025 W as opposed to 1 W for LISA). A group at JPL is also designing a NPRO laser for use in the SIM mission [Ref. F-10]. This laser is designed for a 10-year mission, but presently has no frequency tuning actuators.

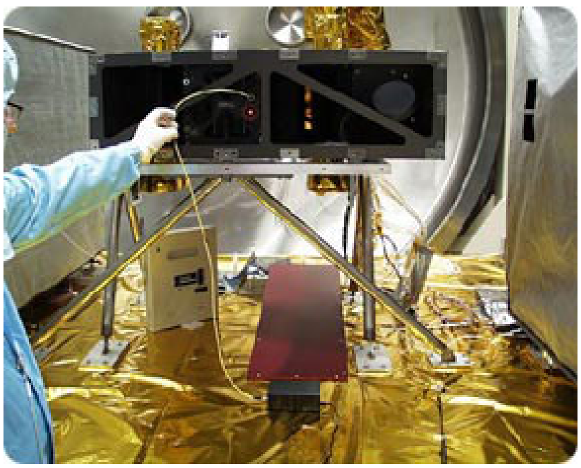


Figure F-13: Lightwave's NPRO laser was space qualified for use on the TES instrument.

Tesat-Spacecom has built and is space qualifying a MOPA laser. The engineering model of the master oscillator has been space qualified for a 10-year mission, and the engineering model of the power amplifier is currently under qualification. Lightwave Electronics is also in the process of space qualifying a MOPA laser for a SBIR-II contract. This laser is scheduled for delivery to JPL in approximately 24 months.

At the beginning of the technology development effort commercial off-the-shelf non-space qualified lasers meeting the LISA requirements were available, so a TRL of 4 was assigned to the laser system. Since then, several components have been space qualified, e.g., the Lightwave Electronics and Bosch master oscillator, thermo-electric cooler, etc. A complete space qualified system has not yet been tested so the TRL remains at 4.

Laboratory laser stabilization measurements were made at the University of Hannover that met the LISA requirements above 200 mHz [Ref. F-6], therefore a TRL of 3 was assigned to the laser stabilization at the beginning of the technology development effort. Several efforts are underway to reproduce and improve upon these results, but these efforts are in the early stages of development. Therefore, the current TRL of the laser stabilization remains at 3.

The heritage of TDI extends from experience with the Cassini mission [Ref. F-11] where correlations were used to remove unwanted effects appearing with well-known time signatures. Subsequent analysis of TDI has shown it to be compatible with schemes for the removal of the optical bench motion [Ref. F-12], and ultra-stable oscillator (USO) noise introduced in compensating for the Doppler shifts [Ref. F-7, Ref. F-13].

At the beginning of the technology development effort the analysis of TDI was sufficient to give it a TRL of 3. Laboratory demonstrations of TDI are underway, but have not yet completed, therefore, the TRL for TDI remains at 3.

A PLL phase meter was developed by JPL for use in the GRACE mission [Ref. F-14]. The main difference between the GRACE phase measurement system and that of LISA is that GRACE uses a much lower baseband frequency (1 MHz).

The phase counting technique is in development at the Joint Institute for Laboratory Astrophysics (JILA) (University of Colorado) for LISA and is shown in Figure F-14. This scheme relies on counting the zero crossings of the beat signal using a fast clock. Fractional cycles at the beginning and end of each time period are measured with a resolution of 10 ps rms. Sampling at a fixed rate of ~100 Hz, and at 10 ps resolution, is consistent with the LISA requirement of 10^{-5} cycles/$\sqrt{\text{Hz}}$.

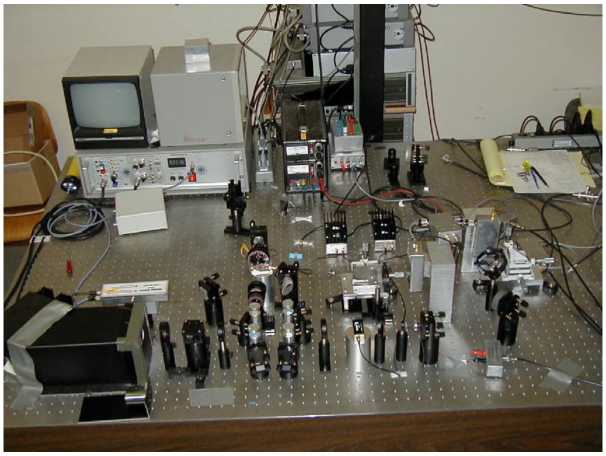


Figure F-14: The JILA counting and timing phase meter has demonstrated a phase noise that meets the LISA requirement.

At the beginning of the technology development effort, both the PLL and counting techniques were at the proof-of-concept level and partial lab verification had been performed, giving them a TRL of 3. Since then, laboratory work on the counting technique produced results consistent with the LISA requirements. Full verification of the techniques is still in process, so the TRL of the current phase measurement system remains at 3.

To minimize the effect of thermal noise coupling into the measurement, ultra-low expansion materials must be used in both the optical system and the telescope structure. Materials being considered include: ULE™, Zerodur™, and fused silica. A space-qualified hydroxy-catalysis bonding technique can be used to attach the optical components to the optical block. All of these materials are common in space applications, but their stability at low frequencies needs to be verified. For this reason a TRL of 5 is assigned to the current status of "ultra-stable structures."

The complete IMS is assigned a TRL of 3, based on the component with the lowest TRL. The total project investment to date in the IMS is about $3.1M.

F.2.2.2 Technology Development Plan

The major risks of the IMS are summarized in Table F-2. The first risk is the laser system not meeting the lifetime requirement. This risk is attributable to the thermo-electric cooler (needed for the frequency control of the pump diodes and the slow actuation of the main laser frequency output) and the high power laser pump diodes. The impact of this risk is a shortened mission lifetime. To mitigate this risk three laser concepts are being developed.

The first laser concept is being developed in conjunction with Tesat-Spacecom GmbH & Co.KG. The components for this laser are in the late stages of space qualification. The main emphasis of the development of this system is performance enhancement. The second and third laser systems are based on the Lightwave design. One system is being developed at Laser Zentrum Hannover and the other at JPL. These systems have demonstrated adequate performance, but have not been space qualified, thus the emphasis of their development is on qualification.

Lifetime testing on the laser component subsystems and on the complete laser systems begins early in the project. Running the laser at a lower power level than its maximum can also increase the lifetime. This results in reduced measurement sensitivity and a consequent reduction of science. The number of laser systems in the mission baseline can also be increased. A larger telescope could also be used to compensate for a lower laser power. These system trades are part of the system engineering activity described in Section E. A down-select of the laser system will occur no later than payload PDR in December 2006.

The main risk in the laser stabilization scheme is that it does not meet the frequency stabilization requirement. This results in an increased requirement on TDI to remove the frequency fluctuations. To mitigate this risk, three laser stabilization efforts are being supported and several others are being tracked.

The three supported efforts at GSFC, the University of Hannover and the University of Glasgow, are working on a combination of cavity and molecular stabilization. As mentioned above, the Hannover experiment has already met the LISA requirements above 200 mHz. The bulk of the stabilization development effort is devoted to extending this result to the full LISA MBW. Research on iodine stabilization at the University of Konstanz, University of Berlin, INNOLIGHT GmbH, and NIST are also being tracked for LISA application.

A key risk of TDI is that it may not remove the frequency noise from the measurement to the required level. This results in a severe impact to the science. To mitigate this risk, extensive analysis of TDI is performed along with electronic and optical tests of the key aspects of TDI. These tests include a Michelson interferometer with a several kilometer arm length mismatch (achieved by the use of optical fibers). Integrated modeling, described below, will also be used to further investigate the application of TDI. This risk is also mitigated by increasing the requirement on the laser stabilization.

The key risk of the phase meter is that it does not meet the phase resolution requirement. The consequence of this risk is reduced measurement sensitivity, thus an impact to the science. To mitigate this risk, four independent phase meters are being considered using different techniques. As mentioned above, JPL is developing the PLL technique and GSFC and the University of Colorado are developing the counting technique. Three other groups at the University of Glasgow, University of Birmingham, and at University of Hannover are also developing phase meters that use similar methods.

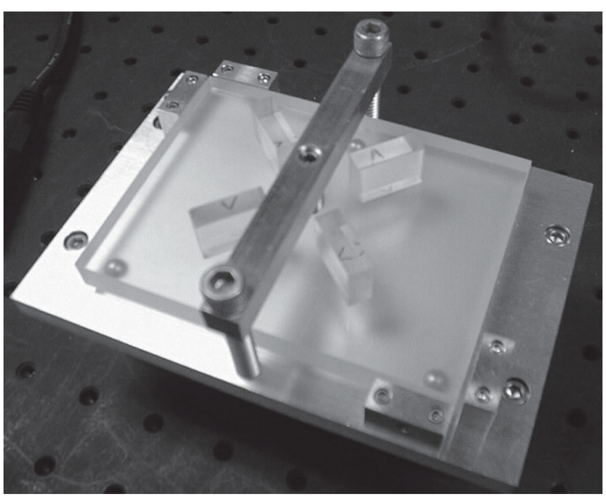


Figure F-15: Initial tests of Hydroxy-catalysis bonded optical components at JPL have demonstrated the required stability.

The last key risk for the IMS is that materials or bonds do not meet the dimensional stability requirement. This results in a severe impact to the science. To mitigate this risk, stability measurements are performed on a number of candidate materials and bonding techniques. An effort at GSFC is looking specifically at the picometer stability of optical materials in the LISA MBW. An effort at JPL is investigating the stability of several optical bonding techniques (Figure F-15). The University of Hannover is looking at stability of materials used for the laser stabilization cavity. Finally, the University of Glasgow and Rutherford Appleton Laboratory in the UK are looking at the stability of optical bonds and their alignments. Hannover and the UK are building the LTP optical bench using these techniques.

As shown in Figure F-3, the first major down-selects occur in March 2004. At this point, the most promising phase meter, laser, and stabilization schemes are identified and work begins on building two prototype IMS, one in the U.S. and one in Europe. Each prototype consists of the optical block structure, but does not include the telescope. An IMS tester that holds the optical block and simulates the incoming laser beam is ready in December 2004. The prototype IMS is tested to full performance and is space qualified by 2006. The final selection of the IMS occurs in August 2006, 4 months prior to payload PDR.

The laser stabilization, phase meter, and ultra-stable structures activities are already underway and do not require any new facilities. The IMS testers require a small clean room with an optical table and vacuum chamber. Most of the laser development is performed at the manufacturers and independent testing requires only tabletop scale setups.

Table F-2: The key risks for the interferometry measurement system are identified. The mitigation steps in place reduce the likelihood to low.

Risk	Impact	Mitigation	Consequence
Laser does not meet lifetime requirement	Shortened mission lifetime	Three independent laser efforts. Early lifetime testing. Increase redundant components in laser design. Increase number of redundant laser systems in mission baseline system trade. Operate laser at a lower power level. System trade to enlarge telescope compensates for power reduction.	Moderate
Laser stabilization does not meet frequency stabilization requirement	Increased requirement on TDI	Three independent stabilization efforts supported. Several others tracked. Increase requirement on TDI system trade.	Minimal
TDI does not meet phase noise cancellation requirement	Severe impact to science	Extensive analysis of TDI. Laboratory tests of TDI. Increase requirement on laser stabilization system trade.	Severe
Phase noise in measurement system does not meet requirements.	Severe impact to science	Four independent phase measurement efforts.	Severe
Materials or bonds do not meet the dimensional stability requirement	Severe impact to science	Three independent stability studies are performed on a number of candidate materials and bonding techniques	Severe

F.2.3 System Verification

The major risks of System Verification are summarized in Table F-3. The precision measurement aspect of LISA makes it particularly important that the system performance be verified prior to launch. An approach that uses a combination of modeling and test is used to give confidence and retire risk. The risk of the system not meeting the on-orbit performance requirements was identified early in the project and a significant fraction of the technology development effort is dedicated to retiring this risk. The following subsections describe the modeling and test bed elements of the technology development effort. Since these technologies are for ground verification, no TRL values are given. However, the current status of the technologies is discussed.

F.2.3.1 Integrated Modeling

Integrated modeling of gravitational wave sources, the payload, the spacecraft, the constellation, as well as the data reduction and analysis, is required to study the performance and system behavior of LISA. This effort incorporates existing modeling tools (e.g., geometric, structural, controls, thermal, orbital), and also creates some new tools such as gravity field modeling.

Detailed integrated modeling of the LISA mission is required for the following reasons: first, the level of interactions between disciplines and subsystems for LISA are more intricate than for traditional space missions. For example, traditional structural, thermal, optical (STOP) analysis must be expanded to include changes in the self-gravity (gravitational attraction of the PM to the spacecraft) due to thermal deformations. Second, the precision and accuracy required from the modeling is more stringent than for most missions. For example, in some parts of the spacecraft the behavior to picometer length changes and microKelvin temperature fluctuations needs to be understood. Finally, the models must complement the test beds and flight demonstrations to predict the on-orbit performance of LISA.

Precision measurements of this type always demand extensive analysis of potential disturbances and systematic effects. Much modeling of acceleration disturbances and measurement noise has already gone into the formulation of the LISA baseline design, however, until recently, these models have been examined within the context of a single subsystem. These models need to be incorporated into conventional integrated modeling of structural, thermal, optical, and control systems to assess their full effects on the interactions of subsystems throughout the spacecraft. For example, thermal variations can have widespread effects through dimensional changes affecting the spacecraft gravitational field, changing primary-secondary separation in the telescope, and unbalanced thermal photon pressure on the proof mass.

Due to the coupling of the LISA subsystems, the integrated modeling effort is used to verify the flow down of requirements to subsystems and components. This approach complements the traditional error-tree analysis. Combined with test bed measurements, the integrated model verifies the elements of the error tree as well as the full system performance.

The requirements for the integrated models are defined as the functions the models must perform. The model fidelity that each function requires is quite varied. The integrated models have different modes of operation to perform these different tasks. The major tasks required of the models are:

- Support trade studies
- Optimize the design before construction
- Develop/validate instrument requirements
- Support technology test beds
- Validate technology flight demonstrations
- Support payload and mission-level integration and test
- Support flight operations
- Support ground calibrations
- Support flight calibrations
- Support science data analysis

Not all of these functions are utilized nor are fully developed during the formulation phase; for example, "support flight operations" need not be fully developed at this point. However, it is important to recognize that the models eventually support these activities so that their implementation can be properly designed into the model architecture.

The integrated model is not a single monolithic model, but rather a library of modeling tools and data that can be configured by users for their individual purposes. There are designated model configurations that represent the reference design.

The top-level elements for the integrated model are: the *modeling environment, quasi-static models, dynamic models, phase propagation models, end-to-end models*, and *test bed models*. These elements are briefly summarized below.

The *integrated modeling environment*, often referred to as an advanced engineering environment, supports the development, execution, user interaction, and archiving of the models. The design of this environment draws upon the experience of the James Webb Space Telescope and the 2nd Generation Reusable Launch Vehicle integrated modeling efforts. The environment houses the collection of modeling tools, including relevant analysis packages, model configurations, input data sets, and an archive of previous model runs. It has a user interface supporting access to the modeling tools and collaboration by the user community. It also provides administration for user access, configuration control, etc.

The *quasi-static* models element contains all models that are independent and quasi-independent of time. This includes not only the traditional structural, thermal, and optical models, but also non-traditional elements like self-gravity and proof mass charging. Integrating these disciplines enables the study of effects such as how changes in shape due to ground-to-orbit cool-down effect the optical path and gravitational field.

The *dynamic* models element contains models that are time-dependent. It combines structural, optical, gravitational, orbits, and controls. An example analysis is to optimize the DRS control system to minimize the disturbance to the proof mass due to articulating the telescope.

The *phase propagation* models element contains the models describing the interferometer measurement system. It models the propagation of the phase and phase noise of the laser beam starting from the laser, through the optical chain, and into the phase meter. It is used to study laser stabilization schemes and laser phase noise cancellation algorithms.

The *end-to-end* models element contains two main components: the system error trees and the science data simulator. The error trees are used for requirement flow down and trade studies. They begin with top-down error budgets and evolve into bottom-up error trees that are fed by simulations and test bed measurements. The science data simulator is used to test the science data analysis package and perform science-based requirement flow down. It contains three components: gravitational wave source models, an instrument response model, and a data analysis package. The development of this tool draws heavily from the scientific community.

The four classes of models described above are not independent. Many of the models developed in each class are used for different analyses within other classes.

The final model element is *test bed models.* This element "anchors" the models to laboratory test beds as part of the model validation and verification plan. As shown in Figure F-16, model results are constantly compared to test bed measurements to ensure fidelity. In addition, the SMART-2 mission represents an excellent opportunity to demonstrate the validity of the models. To take advantage of this opportunity, this element also models the SMART-2 on-orbit performance. This experience provides added confidence over the test beds comparisons that the models for LISA have correctly bridged the gap between ground and on-orbit performance.

F.2.3.1.1 Integrated Modeling Readiness

The LISA application of coupling modeling to test beds to predict on-orbit performance builds upon many successful modeling experiences, such as the Hubble fine pointing system. The LISA integrated model is drawing from other ongoing modeling efforts to maximize the application of lessons learned. A few examples are the LIGO ground-based interferometer control system [Ref. F-15], the James Webb Space Telescope [Ref. F-16], and the 2nd Generation Reusable Launch Vehicle [Ref. F-17] integrated modeling efforts.

Many of the tools for building model elements are available as commercial packages. The ability to integrate these packages varies considerably. In addition, commercial packages do not exist for a few of the elements. The two main missing elements are self-gravity and phase propagation. Custom codes exist for these elements and are currently being adapted for this application. The total project investments to date for integrated modeling are about $1.2M.

F.2.3.1.2 Integrated Modeling Development Plan

A key risk of the integrated model is producing incorrect models. The impact of this risk is a poor understanding of the on-orbit system performance. This risk is mitigated by constant comparisons with laboratory measurements.

As described above, a major element of the modeling effort is modeling of test beds. As the models increase in breadth and depth over time, they are constantly compared to laboratory measurements. This process is shown in Figure F-16.

The long-term development of the models progresses in three phases during project formulation. The first phase establishes the baseline that then evolves to include higher fidelity and more detailed models. The models provide the basis for analysis that ensures the system requirements are meaningful, self-consistent, and verifiable. Sensitivity analyses are performed to determine which requirements are drivers and risk analysis identifies those that are high risk. During this phase, many of the traditional engineering trades are performed. Only a low degree of model integration is implemented at this stage. A major milestone occurs in November 2003 that represents the completion of the requirements validation. At this point there is confidence in the technical requirements and this information is available for the mission-level MCR that occurs one month later in December 2003.

The second phase of the modeling effort is a period of trade studies. Models are built that deviate from the baseline in systematic ways. The models are exercised by system engineering to help drive the design of the instrument. A higher level of integration is implemented to help understand the complex interactions between subsystems. A major milestone occurs in August 2005 that represents the completion of the primary trade-off studies that define the basic design of the LISA mission. It occurs one month before the mission-level SRR that takes place in September 2005.

The third phase of the modeling effort strives towards full integration of the models. A complete science data simulator is developed and the error trees are fully mature. Trade studies are performed that require under-standing the subtle interactions between normally independent subsystems. As PDR approaches, the models are used to refine technical options relative to cost and risk. This round of trade-off assessments ends with a major milestone in April 2007. This milestone directly feeds the mission-level PDR that also occurs later in the same month.

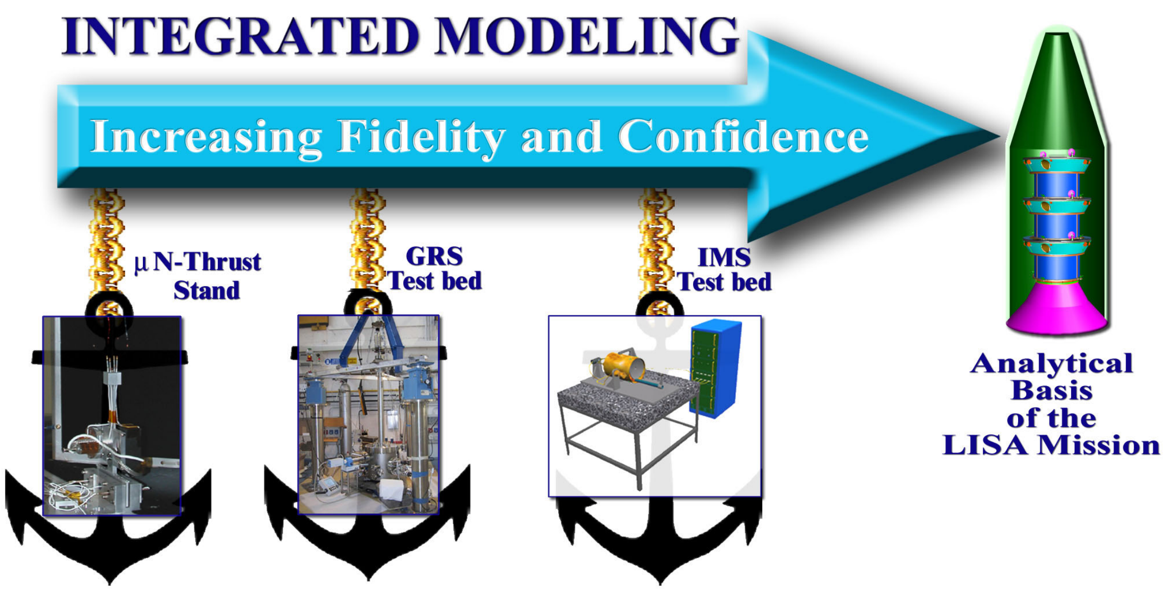


Figure F-16: The models are constantly being compared to test bed measurements to ensure accuracy.

The models produce "synthetic" science data products representative of the real telemetry that are used to test candidate data reduction techniques. There is a major milestone at the end of this task that occurs in April 2007. This milestone represents the final analytical justification of the LISA mission. That is to say, models of the sources, instruments, spacecraft, ground system, and detection algorithms have operated in concert to demonstrate the detection of individual sources as anticipated. This milestone also feeds directly into the mission-level PDR later in the same month.

As the technology test beds are developed, they require modeling support initially to set performance goals and to forecast their performance. The test beds then are used to feed data to the models and provide verification of model accuracy.

The three phases described above carry the modeling effort through Formulation of the project. As the project transitions to Implementation, the modeling effort transitions as well. Emphasis is now placed on supporting the I&T test beds and the science data analysis effort. Hardware-in-the-loop experiments become a major focus for the models. The models are also used to support Operations. Flight software programmers also use the models to develop and test their code.

No major facility investments are required for integrated modeling. Commercial off-the-shelf software is used as much as possible. Conventional server-class computers are more than sufficient for this task. Much of the software and hardware required for this effort already exists at the NASA centers. Initial partnering with other missions has already been established to share the cost of developing common components. For example, the advanced engineering environment used by the 2nd Generation Reusable Launch Vehicle is currently being modified for use by both JWST and LISA on a common server.

F.2.3.2 System Test Bed Technology

The verification plan for LISA uses test beds as an incremental test program. Performance is fully verified at the subsystem level before final integration. At the payload and observatory integration level, a number of end-to-end system tests are performed. Simulators are used to test aspects that require the full sensitivity of the GRS and the 5 million km arms. Early identification of these challenges allows the addition of requirements to the instrument design in order to facilitate the integration and test: "a facile integration is a property of a good design." Early identification of these challenges also provides the time to develop advanced measurement techniques and technologies that enable the testing of instrument performance during I&T to levels not otherwise currently possible.

The test bed element of the technology plan contains the development of these advanced measurement techniques and technologies. Much of the test bed technologies built during the project technology development effort are used in the final I&T test beds, but the construction of these facilities is deferred to Implementation.

The test bed technology and techniques developed in this program are directly tied to testing specific performance requirements of the LISA instrument. The most critical areas of performance measurements that require enabling or extended technologies are: GRS disturbance levels and readout sensitivity, temperature and material stability of the optical block and telescope support structure, aggregate phase noise in the interferometry measurement system, and pointing stability.

F.2.3.3 Technology Readiness

The challenge for developing I&T test bed technology is to take established precision measurement techniques and adapt them for a particular application. A number of these techniques have been identified; this subsection describes the most promising methods.

The *torsion pendulum* has been an essential precision measurement tool for more than 100 years. It provides excellent seismic isolation in one degree of freedom and can be used to monitor torsional displacements down to levels dominated by the thermal motion of the torsion fiber. Shown in Figure F-17, a torsion pendulum is currently being used to test GRS performance.

Figure F-17: GRS performance is demonstrated on an ultra-sensitive torsion pendulum.

Laser interferometry is an essential part of the LISA mission and also plays a critical role in the I&T test beds. Laser interferometry has demonstrated the capability of monitoring displacements to picometers in controlled settings. Experiments at the University of Colorado use laser interferometry to simulate the Doppler motion of the spacecraft and the attenuation of the laser beam due to the 5 million km arm length. Laser interferometry can also be used to monitor temperature stability using an optical cavity.

Active and passive *seismic isolation* can be used to reduce the level of ground vibration that enters into a measurement. Great advances have recently been made in seismic isolation by the ground-based gravitational wave community. Isolation at higher frequencies may enable measurements that would otherwise be dominated by external vibrations. It may not be possible, however, to completely isolate the experiments from ground motion at the very low frequencies of the LISA MBW.

In addition to these specific technologies, there are other precision measurement practices that are included in the development of the I&T test bed techniques. Two examples are common-mode and null measurement techniques. Inclusion of these practices in a test bed design can **eliminate** rather than simply reduce an otherwise dominating noise source. For example, a three-arm test bed first proposed in the 1999 LISA technology plan forms an optical gyro where environmentally caused optical path changes are common-mode and consequently are not a dominant noise source.

F.2.3.4 Technology Development Plan

The key risk associated with the test bed technology is that it will not be possible to build test beds capable of verifying a critical performance requirement before launch. The consequence of this risk is greater uncertainty of system verification before launch. Given that the GRS cannot be operated at full performance on the ground and 5 million km interferometer arms are not practical on Earth, this risk will never be completely eliminated. Therefore, the goal of the test bed technology development effort is to minimize this risk.

History has shown that system test beds often overrun in terms of cost and schedule and ultimately may not test the appropriate system requirements. The strategy outlined below addresses these problems in several ways. First, all test bed designs are tied to system-level performance metrics. A sequence of independent reviews ensures this rule is followed and that all test beds contribute directly to mission success. Second, an incremental approach to test bed development eliminates inadequate designs.

The strategy for the test bed technology element is threefold: *design*, *technique*, and *technology*. Through the *design* of the LISA hardware, features are incorporated that enable the testing of critical performance requirements. One example is adding a micromanipulator to the proof mass caging system that enables testing of the IMS and the GRS displacement sensor. Measurement *techniques* are developed that enable/extend our ability to perform critical tests. These techniques drive the development of *technology* for these measurements. This includes simulators as well as measurement technologies.

The test bed element progresses in two phases. First is a requirements and trade study period. The various measurement techniques discussed above are assessed for their application to LISA I&T. Requirements for the test beds are directly linked to the system-level instrument requirements derived from the science requirements. Strong interaction with the design and modeling teams ensures that the baseline design of the instrument supports the measurement approach. This phase ends in September 2005 prior to the mission SRR. At the SRR, several test bed approaches are selected for detailed study.

During the second phase, the most promising concepts are developed in detail. Again, a strong connection to the modeling group ensures that the approach meets the performance requirements. Part of this phase is the construction and testing of the key test bed technologies. Scaled-down versions of the I&T test beds are built to validate the measurement method and test the simulators and measurement technologies. Ideally these versions are adapted for use in the final I&T test bed that is built after the project enters Implementation. This phase ends in June 2006 with a demonstration of the final test bed concept.

During each of the two phases outlined above, an independent review panel monitors the progress of each test bed development. This panel is composed of technical experts who assess the feasibility of any test bed approach. The review panel and test bed teams also coordinate with the SE Office to ensure that the test beds address critical system-level performance metrics.

During the first phase of this development no hardware is built so no special facilities are required. During the second phase only modest facilities are required for the concept demonstrations. A typical facility is similar to that required for the IMS tester described above: a small clean room with an optical table and vacuum chamber.

Table F-3: The key risks for system verification technologies are identified. The mitigation steps in place reduce the likelihood to low.

Risk	Impact	Mitigation	Consequence
Integrated modeling produces incorrect models.	Poor understanding of the on-orbit system performance	Constant comparisons of models to laboratory measurements. Regular reviews by independent experts.	Moderate
Test beds unable to meet requirements for full performance testing before launch	Greater uncertainty of system verification before launch	Several independent testing strategies developed. Aggressive integrated modeling effort. Test beds are part of an incremental test program. Coordinated design, system engineering, technology development, modeling, and I&T activities early in the program.	Moderate

F.3 Other Program Formulation Activities

The LISA Formulation Phase begins in February 2004 and captures the conceptual design and technology momentum into a design meeting all constraints. This phase establishes requirements and success criteria, converts the current mission concepts into an optimized technical design, and conducts reviews that systematically guide the project towards approval and implementation in October 2007.

Formulation ends with all activities completed for a successful PDR and NAR in April 2007. System Engineering, supported by the SE&I contractor, has completed all trade studies, requirements flow down, and has selected the baseline system architecture. All payload subsystem engineering model elements are designed and are in a late stage of testing.

The technology development effort is complete by the end of 2006. As described in the previous subsections, all technologies are at TRL 6 by this time. The DRS is at TRL 5 by June 2005 and is at TRL 6 by November 2006. The IMS is at TRL 5 by April 2005 and is at TRL 6 by August 2006. The integrated model has completed three phases of development by April 2007. The integration and test concepts are fully developed and their approach validated by June 2006.

Payload requirement flow down and architecture trades are complete by the Payload PDR in 2006. The detailed designs and development of the engineering models of the DRS, IMS, and Y-tube assembly are started in September 2005, once all technologies have achieved TRL 5. These models feed the flight builds that commence after Mission PDR.

F.3.1 Formulation Strategy

Central to formulation strategy is the synergy between system engineering studies and the technology development effort. These two activities assure mission success by maintaining reserves, slack, and alternatives with concrete decision points that provide viable off-ramps.

An end-to-end error tree is built as part of the integrated modeling effort to provide a tool that turns the science input into subsystem performance and error allocations. The system engineering team uses this tool to complete and validate the requirements flow down. Results from the technology test beds are iterated with the models to ensure model accuracy. For example, the contribution of patch fields to the acceleration noise budget is confirmed using the torsion pendulum measurements at the University of Washington (see Section F.2.1.2).

The modeling environment discussed in Section F.2.3.1 uses the project internal web site as an interface to the end-to-end error trees. Scientists and outside experts are given access to these tools to provide additional checks and exercises for the models. The models and inputs are fully documented and many of the derivations and measurements are published in publicly accessible journals and technical reports.

Once the requirements flow down is complete, the error trees are used to perform a number of trade studies. These studies provide off-ramps for any technology that is falling short of its requirements. These off-ramps provide the rationale for reallocation of resources and reserves to design solutions that can offset a technology shortfall.

One example of this process is in addressing the risk that the laser system does not meet power and lifetime requirements. To extend the lifetime, the laser can be operated at a lower power level. The diameter of the telescope can be increased to compensate for reductions in laser power. However, this increases the requirements on the telescope pointing. If the pointing system can be improved to meet the new requirements, this trade provides an off-ramp for the laser development work.

The SE&I contractor provides top-level system design to verify and complement the design studies already performed by European industry. This provides an independent verification that the specifications in the European Invitations To Tender meet the overall mission requirements. It tracks the performance of the integrated system using the error tree plus other system engineering tools. The SE&I contractor works closely with the integrated modeling team to benefit from the strong mix of engineers and physicists already in place.

The final technology down-selects occur prior to the Technology Readiness Review in November 2006. NASA and ESA have already agreed on a preliminary allocation of payload components. These allocations are finalized prior to Payload PDR in December 2006. The process for arriving at the final flight system delivery responsibilities includes the following:

- Parallel technology development in both Europe and in the U.S. Both sides collaborate with coordinated similarities and differences.
- An integrated design team develops the payload design.
- Preliminary flight system delivery responsibilities are based on maximizing test coverage and minimizing integration and test risks.
- Those who do not have flight system delivery responsibilities may still deliver flight systems based on the demonstrated merit of their technologies.
- Technology providers who are not contributing to the flight system delivery contribute to ground systems such as simulators, test systems, and tools.
- Most European and U.S. technologies will merge for flight delivery. When technology down-selection is needed, ESA and NASA assign an independent selection committee.

This approach has the benefit of:

- Keeping all technology contributors involved in the mission
- Maximizing innovation
- Stimulating European member-state contributions
- Assigning clear responsibility and accountability for flight delivery

F.3.2 Formulation Products

The LISA Formulation approach is fully compliant with the requirements of NPG 7120.5, NASA Program and Project Management Processes. As such, it consists of a comprehensive set of processes, reviews, and documents in addition to the technology and system engineering products discussed above.

The technology development effort produces all of the required technologies with TRL 6 by 2006.

Many of the system engineering products are discussed in Section E. These products are fully compliant with NPG 7120.5 and include:

- Flight, ground, and launch requirements
- System engineering management plan
- Spacecraft and payload concepts
- Verification matrix
- Resource allocations
- Risk management plan
- IV&V of flight software
- Data policy

Project planning develops the detailed definition of the project requirements and establishes project control to manage the other formulation processes. Major activities include formation of the project team, development of the Project Plan, identification and refinement of life cycle costs, schedules, risks, and performance baselines, as well as definition of project success criteria. A number of management and planning formulation products are produced in compliance with NPG 7120.5 including:

- LOA with partners
- International management agreement
- NASA/ESA MOU
- Integrated schedules
- Science management plan
- Flight assurance/safety approach
- Independent external reviews plan

- E&PO plans
- WBS
- Acquisition strategy

The LISA Project conducts eight major project-level reviews with NASA-chartered panels and scientific advisory committees composed of private industry experts, retired NASA personnel, and ESA representatives. These reviews reflect the successive refinement of the current mission design into an optimized technical design, which becomes the baseline in preparation for project approval. Throughout this process, advice and recommendations from the review teams are integrated into the planning process. These reviews are shown on the master and integrated schedules in the appendix and are summarized in Table F-4.

Table F-4: The LISA Project's thorough review process assures organizational and technical readiness.

Review	Date
Mission Concept Review (MCR)	12/03
Mission Definition Review (MDR)	5/05
Initial Confirmation Review (ICR)	8/05
Confirmation Assessment (CA)	8/05
System Requirements Review (SRR)	9/05
System Concept Review (SCR)	12/05
Technology Readiness Review (TRR)	11/06
Non-Advocate Review (NAR)	4/07
Preliminary Design Review (PDR)	4/07

During the formulation phase, the LISA Project Team prepares the documents needed to proceed in an orderly manner into the Implementation Phase. Table F-5 summarizes some of the documentation that the LISA Project will prepare along with the due dates.

Table F-5: Planning documents are prepared by the Project to proceed in an orderly manner into the Implementation Phase

Document	Due
Risk Management Plan	SRR
Software Management Plan	MDR
Configuration Management Procedure	SRR
Environmental Assessment	SCR
Mission Assurance Requirements	PDR
Orbital Debris	PDR
Program Plan	PDR/ NAR
Project Plan	Draft prior to NAR
Safety Data Packages	MDR
Software Requirements Document	PDR
Software Test Plan	PDR
System Engineering Management Plan	PDR
Technology and Commercialization Plan	PDR/ NAR